Variable Rainfall Intensity and Tillage Effects on Runoff, Sediment, and Carbon Losses from a Loamy Sand under Simulated Rainfall

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The low-carbon, intensively cropped Coastal Plain soils of Georgia are susceptible to runoff, soil loss, and drought. Reduced tillage systems offer the best management tool for sustained row crop production. Understanding runoff, sediment, and chemical losses from conventional and reduced tillage systems is expected to improve if the effect of a variable rainfall intensity storm was quantified. Our objective was to quantify and compare effects of a constant (I_c) intensity pattern and a more realistic, observed, variable (I_v) rainfall intensity pattern on runoff (R), sediment (E), and carbon losses (C) from a Tifton loamy sand cropped to conventional-till (CT) and strip-till (ST) cotton (*Gossypium hirsutum* L.). Four treatments were evaluated: CT-I_c, CT-I_v, ST-I_c, and ST-I_v, each replicated three times. Field plots (n = 12), each 2 by 3 m, were established on each treatment. Each 6-m^2 field plot received simulated rainfall at a constant (57 mm h^{-1}) or variable rainfall intensity pattern for 70 min (12-run ave. = 1402 mL; CV = 3%). The I_v pattern represented the most frequent occurring intensity pattern for spring storms in the region. Compared with CT, ST decreased R by 2.5-fold, E by 3.5-fold, and C by 7-fold. Maximum runoff values for I_v events were 1.6-fold higher than those for I_c events and occurred 38 min earlier. Values for E_{tot} and C_{tot} for I_v events were 19–36% and 1.5-fold higher than corresponding values for I_c events. Values for E_{max} and C_{max} for I_v events were 3-fold and 4-fold higher than corresponding values for I_c events. Carbon enrichment ratios (CER) were ≤1.0 for ST plots and ≥1.0 for CT plots (except for first 20 min). Maximum CER for CT-I_c, CT-I_v, ST-I_c, and ST-I_v were 2.0, 2.2, 1.0, and 1.2, respectively. Transport of sediment, carbon, and agrichemicals would be better understood if variable rainfall intensity patterns derived from natural rainfall were used in rainfall simulations to evaluate their fate and transport from CT and ST systems.

Coastal Plain soils in Georgia have traditionally been intensively cropped under conventional tillage practices, have relatively sandy surfaces, tend to be drought prone, and are susceptible to compaction/consolidation and runoff and sediment and chemical losses. Our understanding of these losses from different tillage systems is expected to be improved if the effect of variable rainfall intensity during a storm is quantified.

Rainfall characteristics influence processes affecting infiltration, runoff, soil detachment, and sediment and chemical transport. Rainfall intensity is a major factor influencing soil erosion, especially interrill erosion (Meyer and Harmon, 1989; Truman and Bradford, 1993) because it affects soil detachment by raindrop impact and transport of detached particles by runoff. Rainfall simulators have been used extensively to evaluate rainfall characteristics on runoff, sediment, and chemical transport (Wan and El-Swaify, 1998; Truman et al., 1998; Potter et al., 2003; Truman et al., 2003; Potter et al., 2004). Simulated rainfall is more repeatable and controllable than natural rainfall. Most studies using simulated rainfall to investigate processes controlling runoff and erosion apply rainfall at different rainfall intensities, yet all are at a constant rate. Few studies have investigated runoff and erosion with a rainfall simulator using variable rainfall intensity (Frauenfeld and Truman, 2004). Natural rainfall is variable, spatially and temporally (Rao and Chenchayya, 1974; Carter et al., 1974; Flanagan et al., 1988; Bosch et al., 1999; Frauenfeld and Truman, 2004). The frequency of severe rainfall events has increased throughout the USA, including the Southeast, due to increased intensity of heavy or extreme rainfall events (Karl and Knight, 1998; Groisman et al., 2001; Todd et al., 2006). Changes in rainfall intensity within a storm affect how rainfall is partitioned between infiltration and runoff, and subsequent sediment and carbon yields (Flanagan et al., 1988; Romkens et al., 2001; Frauenfeld and Truman, 2004; Strickland et al., 2005).

The highly weathered soils in the Coastal Plain region of the Southeast benefit from reduced tillage systems because these sys-

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Abbreviations: C, carbon loss; CER, carbon enrichment ratio; CT, conventional tillage; CV, coefficient of variation; E, sediment yield; I_c, constant rainfall intensity; INF, infiltration; I_v, variable rainfall intensity; P, paratill; R, runoff; Rs, residue; ST, strip tillage.

tems reduce runoff and sediment, enhance infiltration, and increase soil resistance to detachment and subsequent transport (Yoo and Touchton, 1988; Seta et al., 1993; Potter et al., 1995; Truman et al., 2005). Reduced tillage systems accumulate residue and increase organic carbon at the soil surface with time, which helps dissipate raindrop impact energy and increase soil resistance, thus maintaining infiltration and decreasing soil detachment, sediment transport, and water-dispersible clay (Reeves, 1997; Shaw et al., 2002; Truman et al., 2003; 2005).

Conversely, some studies have shown that less runoff (more infiltration) occurs from conventional-till (CT) systems than from reduced-till systems (Heard et al., 1988; Soileau et al., 1994; Cassel and Wagger, 1996), especially 1 to 3 yr after reduced tillage establishment. These results have been attributed to increased consolidation or compaction (NeSmith et al., 1987; Radcliffe et al., 1988). As a result, some form of deep tillage is needed to disrupt the dense, water-restrictive subsurface horizons/zones. This was the case at the study site discussed in this paper. After 4 yr of strip tillage (ST) without paratilling, bulk density values for ST in the top 40 cm of soil were 15 to 25% higher than bulk density values for CT. Also, in the ST system, bulk density values for between-row (row middles) were about 20% higher than values from within-row. After fall paratilling in 2002, bulk density values for the ST system were at least 15% less than bulk density values for ST or CT systems that had not been paratilled. Subsequently, disrupting compacted or consolidated horizons/zones via paratilling reduces bulk density and cone index (Bicki and Guo, 1991; Pierce and Burpee, 1995; Truman et al., 2003, 2005), increases infiltration, and decreases runoff (Sojka et al., 1993; Rawitz et al., 1994; Schwab et al., 2002; Truman et al., 2003, 2005).

In the Southeast, carbon loss in runoff contributes to facilitated agrichemical transport and limits soil organic carbon accumulation at the surface of most agricultural soils. Most carbon loss during an erosive rainfall event is in the sediment/particulate phase (Lowrance and Williams, 1988; Schreiber and McGregor, 2002). For most sediment-transported carbon, the sediment is enriched in carbon when compared with the original soil (Owens et al., 2002; Cogle et al., 2002; Polyakov and Lal, 2004). However, Strickland et al. (2005) found that this is not always the case in Coastal Plain soils because sediment exported from the conventionally tilled Tifton loamy sand under lab conditions was enriched (enrichment ratio = 1.2–1.8), whereas sediment exported from the conventionally tilled Greenville sandy clay loam was depleted (enrichment ratio = 0.8–0.9). They suggested that factors affecting detachment and transport thresholds for sediment and sediment-transported carbon during a rainfall event will affect enrichment characteristics for a given soil and subsequently will affect sediment-transported contaminants.

Quantifying runoff, sediment, and carbon losses from different tillage systems would be improved if the effect of variable rainfall intensity during a storm event was investigated. Our objective was to quantify and compare effects of a constant (I_c) rainfall intensity pattern and a more realistic, observed, variable (I_v) rainfall intensity pattern on runoff, sediment, and carbon losses from a Tifton loamy sand cropped to cotton (*Gossypium hirsutum* L.) and managed under CT and ST systems. Nutrient

and pesticide runoff data collected during our study are described in companion papers (Franklin et al., 2006; Potter et al., 2006).

Materials and Methods

The study site was located at the Univ. of Georgia's Gibbs Farm near Tifton, GA (N 31° 26′, W 83° 35′). The Tifton loamy sand (Plinthic Kandiudult) had a 2 to 4% slope. At the time of site establishment, physical and chemical properties of the conventionally tilled Ap horizon (0–25 cm) of the Tifton loamy sand were 820 g kg^{-1} sand, 70 g kg^{-1} clay, 5.1 g kg^{-1} organic carbon, and pH 5.9. Dispersed particle size was determined by the hydrometer method (Day, 1965), organic carbon was measured by the modified Walkley–Black method (Nelson and Sommers, 1982), and pH (5 parts H$_2$O:1 part soil) was measured in H$_2$O (McLean, 1982). Organic carbon values for CT (0.75%) and ST (0.90%) treatments were determined with a Carlo Erba Model NA 1500 series 2 CN analyzer.

Historical details for the study site have been presented by Potter et al. (2003, 2004) and Bosch et al. (2005). Briefly, since 1998, the Tifton loamy sand has been managed under CT and ST systems in a cotton-peanut rotation (3-yr cotton:1-yr peanut). Tillage treatments included conventional tillage with rye (*Secale cerale* L.) surface cover and without paratilling (CT+Rs-P) and strip tillage with rye surface cover and with paratilling (ST+Rs+P). Conventional till consisted of fall disking, winter rye cover, followed by spring disking and cultivator leveling. Rye surface cover was incorporated ~10 to 15 cm in CT plots. Strip till consisted of planting a winter rye cover immediately after crop harvest and killing the rye with a chemical burn-down treatment about 30 to 40 d before planting the next year's row crop. The ST treatment was paratilled to a depth of 35 to 40 cm before the experiment started in the fall of 2002. Immediately after cotton (*Gossypium hirsutum* L.) was planted in 2003, 12 aluminium 2- by 3-m simulation plots were established on an area 30 m wide by 145 m long that was evenly divided lengthwise between CT+Rs-P and ST+Rs+P plots. For this study, ST+Rs+P plots had organic carbon values of 8.4 and 5.4 g kg^{-1} for the 0- to 1-cm and 1- to 3-cm soil depths and ~4000 kg ha^{-1} of surface residue cover. With ST, the residue cover was not distributed evenly across simulator plots because a 10- to 12-cm wide zone was tilled and used to plant the crop into.

The oscillating-nozzle rainfall simulator (Frauenfeld and Truman, 2004) with 80150 veejet nozzles (median drop size, 2.3 mm) was placed 3 m above each 2- by 3-m plot. Simulated rainfall was applied at a constant (57 mm h^{-1}) and variable rainfall intensity pattern (Fig. 1). The I_v pattern was developed after analysis of measured 5- and 1-min natural rainfall data (30 yr) collected at Tifton, GA (Frauenfeld and Truman, 2004; Strickland et al., 2005; Franklin et al., 2006; Potter et al., 2006). Natural rainfall during the months of March, April, and May were analyzed to determine the pattern that occurred most frequently during the row-crop planting season. Parameters (I_{max}, time to I_{max}, Precip$_{max}$, duration) were then averaged for the group of natural storms occurring most often during this 3-mo period (91 storms). The individual storm with the most parameters similar to the average of the entire group was selected, and its pattern was programmed into the simulator on a

1-min basis as the I_v pattern (Fig. 1). The pattern selected (Fig. 1) does not represent the highest intensity observed (183 mm h^{-1}) but closely represents 27% of the springtime storms sampled from the 30-yr data record. The I_c pattern was determined from the statistical average of the I_v pattern. Rainfall duration for each simulation was 70 min. Total rainfall volume applied over the 70-min duration was the same for I_c and I_v patterns (12-run ave. = 1402 mL; CV = 3%). Water for each simulation was obtained from a nearby groundwater well (depth = 166 m, Floridian aquifer). Before simulating rainfall, antecedent water content was determined gravimetrically (Gardner, 1986) at 0- to 1-cm and 1- to 15-cm depths from five locations surrounding each 2- by 3-m plot. This border area was treated identically to the plot area, including receiving the same distribution of simulated rainfall. Runoff (R) and E were measured at 5-min intervals throughout each simulation and were determined gravimetrically. Because of time till runoff, sediment yield during the first 10 min of each run was assumed representative of splash sediment amounts among treatments. Runoff was collected at the downslope end of each 2- by 3-m plot. Infiltration (INF) was calculated as the difference between rainfall and runoff.

Runoff samples were treated with five drops of concentrated HCl to flocculate sediment and allowed to settle at room temperature for 24 h. A 20-mL sample was taken from the first bottle of each 5-min sampling interval and stored at 20°C until analyzed for dissolved organic carbon (within 48 h) using a Shimadzu TOC 5000 DOC analyzer (Shimadzu Scientific Instruments, Columbia, MD). Remaining water was decanted and discarded. Bottles were oven-dried (105°C for 24 h), and sediments were determined gravimetrically from all bottles and summed within a 5-min sampling interval. Analysis of soil and sediment carbon was determined on ball-milled 5-min samples using a Carlo Erba Model NA1500 series 2 C-N analyzer.

Each tillage-intensity treatment (CT-I_c, CT-I_v, ST-I_c, ST-I_V) was replicated three times for a total of 12 field plots and/or simulations (two tillage systems × two intensity patterns × three replicates). Regression analysis was used to determine relationships between dependent and independent variables. Means and cv (%) are given for measured data. Unpaired t tests were performed, and the probability level used in evaluating the test statistics was $P = 0.05$, unless otherwise noted. All data analysis were conducted with functions in Corel WordPerfect Office 2000 QUATTRO Pro 9.

Results and Discussion

Runoff

Runoff (R), sediment yield (E), and carbon loss (C) for each rainfall intensity and tillage treatment are given in Table 1 and in Fig. 1–3. Total runoff (R_{tot}) for constant intensity (I_c) events was 4 to 10% higher than that for variable intensity (I_v) events, yet differences were not significant among the two tillage treatments ($P = 0.7780$ for CT; $P = 0.2000$ for ST) (Table 1). For I_c and I_v events, R_{tot} values for CT plots were at least twofold higher than those for ST values ($P = 0.0005$–0.0012). Thus, tillage effects on runoff were greater than rainfall intensity pattern effects.
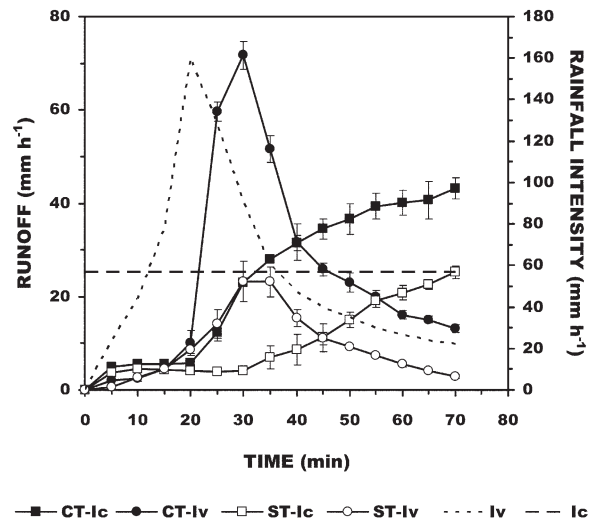

Fig. 1. Simulated rainfall intensity patterns applied and runoff rates from the Tifton loamy sand for each rainfall intensity pattern (I_c, constant rainfall intensity; I_v, variable rainfall intensity) and tillage (CT, conventional tillage; ST, strip tillage) treatments studied. Bars = SE. Note differences in scale between simulated rainfall and runoff.

Table 1. Mean runoff (R), sediment (E), and carbon (C) losses (coefficients of variation) from the Tifton loamy sand for the tillage and rainfall intensity pattern treatments studied.

Parameter†	CT-I_c	ST-I_c	CT-I_v	ST-I_v
Runoff				
R_{tot}, mm h^{-1}	25 (6)	11 (5)	24 (6)	10 (15)
R_{max}, mm h^{-1}	44 (8)	25 (7)	72 (3)	25 (24)
tR_{max}, min	68 (3)	70 (0)	30 (0)	32 (7)
R_{35}, %	24 (12)	21 (4)	58 (1)	58 (7)
R_{70}, %	76 (4)	79 (1)	42 (2)	42 (9)
Soil loss				
E_{tot}, g	1413 (16)	339 (10)	1686 (31)	462 (10)
E_{max}, kg m^{-2} h^{-1}	0.42 (20)	0.09 (13)	1.40 (26)	0.26 (6)
tE_{max}, min	37 (6)	48 (5)	26 (9)	30 (0)
E_{35}, %	37 (17)	33 (9)	80 (3)	70 (3)
E_{70}, %	63 (10)	67 (5)	20 (13)	30 (7)
Carbon loss				
C_{tot}, mg	15 855 (11)	1896 (19)	23 904 (34)	3296 (20)
C_{max}, mg m^{-2} h^{-1}	4329 (30)	615 (34)	18 821 (40)	2657 (11)
tC_{max}, min	45 (22)	53 (14)	27 (11)	30 (0)
C_{35}, %	28 (24)	26 (11)	83 (33)	83 (23)
C_{70}, %	72 (7)	74 (29)	17 (37)	17 (5)

† R_{tot}, total runoff; R_{max}, maximum 5-min runoff rate; tR_{max}, time of R_{max}; R_{35}, percentage of R_{tot} that ran off during the first half (0–35 min) of each event; R_{70}, percentage of R_{tot} that ran off during the last half (35–70 min) of each event; E_{tot}, total soil loss for each event; E_{max}, maximum 5-min soil loss rate during each event; tE_{max}, time of E_{max}; E_{35}, percentage of E_{tot} that occurred in the first half (0–35 min) of each event; E_{70}, percentage of E_{tot} that occurred in the last half (35–70 min) of each event; C_{tot}, total carbon loss for each event; C_{max}, maximum 5-min carbon loss rates during each event; tC_{max}, time of C_{max}; C_{35}, percentage of C_{tot} that occurred in the first half (0–35 min) of each event; C_{70}, percentage of C_{tot} that occurred in the second half (35–70 min) of each event.

‡ CT, conventional tillage; ST, strip-tillage; I_c, constant rainfall intensity; I_v, variable rainfall intensity.
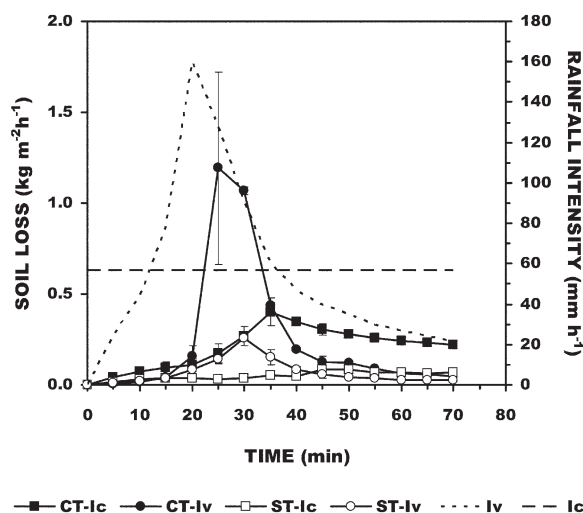
Fig. 2. Sediment yield rates from the Tifton loamy sand for each rainfall intensity pattern (I$_c$, constant rainfall intensity; I$_v$, variable rainfall intensity) and tillage (CT, conventional tillage; ST, strip tillage) treatments studied. Bars = SE.

Differences occurred in runoff rates (Fig. 1) among intensity and tillage treatments. During the first 20 min of rainfall, <10 mm h^{-1} runoff was measured for intensity patterns and tillage systems. After 20 min, runoff rates for I$_c$ events gradually increased throughout the entire simulation duration (70 min). Conversely, runoff rates for I$_v$ events increased sharply from 20 to 35 min and then gradually declined. Runoff curves for I$_v$ events had similar shapes as that for the rainfall intensity curve and lagged intensity curves by 10 to 15 min (peak rainfall intensity occurred at 20 min and peak runoff occurred at 30 min for CT-I$_v$ plots and at 35 min for ST-I$_v$ plots). For CT and ST, runoff curves for I$_c$ and I$_v$ events had similar shapes, yet for a given intensity pattern, runoff rates were always higher for CT plots.

For CT, maximum 5-min runoff rate (R$_{max}$) for I$_v$ events was 1.6-fold higher (P = 0.0008) than that for I$_c$ events (Table 1). However, for ST, R$_{max}$ values for I$_c$ and I$_v$ events were simi-
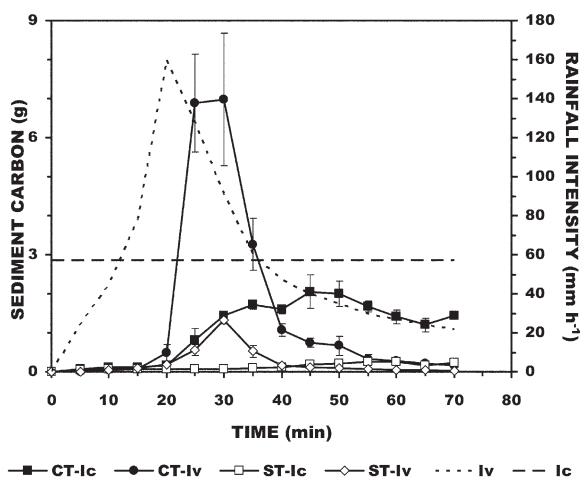

Fig. 3. Sediment carbon rates from the Tifton loamy sand for each rainfall intensity pattern (I$_c$, constant rainfall intensity; I$_v$, variable rainfall intensity) and tillage (CT, conventional tillage; ST, strip tillage) treatments studied. Bars = SE.

lar. For CT and ST, R$_{max}$ values for I$_v$ events occurred 38 min before that of the I$_c$ events (P = 0.0018). For I$_c$ and I$_v$ events, R$_{max}$ values for CT plots were 1.8 to 2.9 times higher than those for ST plots (P = 0.0075–0.0018). For I$_c$ and I$_v$, CT and ST plots had similar tR$_{max}$ values.

Sediment Yield

Total sediment yield (E$_{tot}$) for variable intensity (I$_v$) events were 19 to 36% higher than that for constant intensity (I$_c$) events, yet differences were not always significant (P = 0.5440 for CT; P = 0.0351 for ST) (Table 1). For I$_c$ and I$_v$ events, E$_{tot}$ values for CT plots were at least 3.5-fold higher than those for ST values (P = 0.0030–0.0225). Tillage effects on sediment yield were greater than rainfall intensity pattern effects.

Differences were found in sediment rates (Fig. 2) among intensity and tillage treatments. Sediment curves for I$_v$ events mimicked the rainfall intensity curve and runoff curves (Fig. 1). Sediment curves lagged rainfall intensity curves by 5 to 10 min (peak rainfall intensity occurred at 20 min, and peak sediment yield occurred at 25 min for CT-I$_v$ plots and at 30 min for ST-I$_v$ plot).

Maximum 5-min sediment yield rate (E$_{max}$) for CT-I$_v$ events was 3.3-fold higher (P = 0.0686) than those for CT-I$_c$ events (Table 1). Likewise, E$_{max}$ values for ST-I$_v$ events were 2.8-fold higher (P = 0.0003) than those for ST-I$_c$ events. For CT and ST, E$_{max}$ values for I$_v$ events occurred 4 to 11 min before that of I$_c$ events (P = 0.0082–0.0132). For I$_c$ and I$_v$ events, E$_{max}$ values for CT plots were at least fourfold higher than those for ST plots (P = 0.0489). For I$_c$ events, ST plots had higher tE$_{max}$ values than CT plots (P = 0.0078). For I$_v$ events, CT and ST plots had tR$_{max}$ values that varied by 15% (NS).

Carbon Loss

Total carbon losses (C$_{tot}$) for variable intensity (I$_v$) events were 1.5 to 1.7 times higher than that for constant intensity (I$_c$) events (P = 0.1660 for CT; P = 0.0320 for ST) (Table 1). For I$_c$ and I$_v$ events, C$_{tot}$ values for CT plots were at least 7.2 to 8.3 times higher than those for ST plots (P = 0.0001–0.0110). Tillage affected C$_{tot}$ values more than rainfall intensity pattern. If we assume that carbon export is linearly proportional throughout a landscape, estimated carbon export potential for ST-I$_c$, ST-I$_v$, CT-I$_c$, and CT-I$_v$ would be 316, 549, 2642, and 3220 kg ha^{-1}, respectively.

Differences occurred in carbon loss rates (Fig. 3) among intensity and tillage treatments. For I$_c$ events, sediment carbon losses during the first 20 min of rainfall were low (<0.15 g for CT plots and <0.08 g for ST plots). From 20 to 70 min, sediment carbon losses for CT-I$_c$ plots increased at a higher rate than those for ST-I$_c$ plots, with sediment carbon loss curves for CT-I$_c$ and ST-I$_c$ plots reaching quasi-steady state. Conversely, for I$_v$ events, sediment carbon losses for CT and ST gradually increased during the first 20 min. At 20 min, sediment carbon losses for CT-I$_v$ plots increased dramatically to a maximum at 30 min and then declined sharply. At 20 min, sediment carbon losses for ST-I$_v$ plots continued to increase gradually to a maximum at 30 min and then declined sharply. Sediment carbon loss curves for I$_v$ events were similar to curves for rainfall intensity, runoff (Fig. 1), and sediment yield (Fig. 2).

Maximum 5-min sediment carbon loss rates (C_{max}) for I_v plots were at least fourfold higher ($P = 0.0010–0.1000$) than those for I_c plots (Table 1). For I_c and I_v events, C_{max} values for CT plots were at least sevenfold higher than those for ST plots ($P = 0.0080–0.0370$). For CT and ST, C_{max} values for I_v events occurred 18 to 23 min before that of I_c events ($P = 0.0339–0.0927$). For I_c and I_v, tC_{max} values for ST plots were 11 to 18% longer than CT plots (NS).

Carbon Enrichment Ratios

Carbon enrichment ratio (CER) values are given for each tillage and rainfall intensity pattern (Fig. 4). Carbon enrichment ratio curves for CT-I_c plots remained <1 and gradually increased during the first 20 min, whereas CER curves for ST-I_c plots peaked (CER = 0.75) during the first 5 min and gradually declined until late in the event (50–70 min). At 20 min, CER curves for CT-I_c plots increased to a maximum (2) at 50 min and remained relatively constant for the rest of the duration. Carbon enrichment ratios for CT-I_c plots were higher than those for ST-I_c plots and remained >1 from 20 to 70 min, whereas CER values for ST-I_c plots had only one value >1 (1.02) at 60 min. For CT and ST, CER curves for I_v events had similar shapes as those for the I_c event during the first 20 min. At 20 min, CER curves for CT-I_v plots increased dramatically to a maximum (2.2) at 35 min and declined sharply to ∼1 at the end of the event. At 20 min, CER curves for ST-I_v plots also increased dramatically to a maximum of 1.2 at 30 min and then declined sharply to 0.4 at the end of each event. Carbon enrichment ratios for CT-I_v plots were higher than those for ST-I_v plots ($P = 0.0370$) and remained >1 from 20 to 55 min, whereas CER values for ST-I_v plots had only one CER value (1.20) at 30 min >1. There were no significant differences in CER values between I_c and I_v for either tillage system ($P = 0.8060$ for CT; $P = 0.4370$ for ST).

Soil Surface-Tillage-Rainfall Intensity Interactions

Conservation tillage, in the form of ST, decreased runoff by 2.5-fold, sediment by 3.5-fold, and sediment carbon by 7-fold and increased antecedent water content (0–1 cm) by 43% ($P = 0.0758$). Strip-till plots had on average 82% of the total amount of rainfall that fell to infiltrate, compared with 58% for CT plots. Assuming that all infiltration is available for crop use and that ET = 6 mm d^{-1}, ST plots would have 42% more days of water for crop use compared with CT plots. Differences in infiltration, runoff, sediment, and carbon losses for the Tifton loamy sand can be explained, in part, by differences in how the two tillage systems partition rainfall as a result of soil surface alteration and disturbance and rainfall intensity pattern. For example, the difference between INF$_{max}$ and INF$_{min}$ (d INF) was at least 1.6-fold higher for CT-I_v than for CT-I_c events. Also, CT plots had d INF values that were 1.8 to 2.8 times higher than d INF values for ST plots. Values for d INF have been related to degree of surface alteration (surface sealing) (Truman and Bradford, 1993; Frauenfeld and Truman, 2004) with larger values of d INF proportional to or indicative of greater alterations or changes in a soil's surface due to raindrop impact. Thus, CT and I_v treatments resulted in the largest change in the surface soil of the Tifton loamy sand.
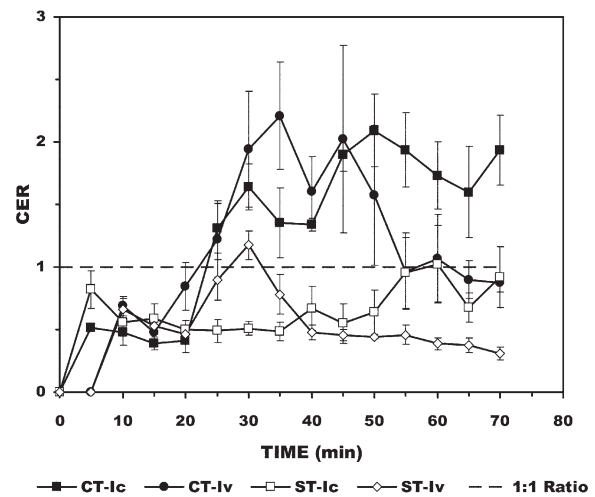

Fig. 4. Sediment carbon enrichment ratios (CER) from the Tifton loamy sand for each rainfall intensity pattern (I_c, constant rainfall intensity; I_v, variable rainfall intensity) and tillage (CT, conventional tillage; ST, strip tillage) treatments studied.

Tillage and intensity pattern effects on runoff, sediment, and carbon losses can be further illustrated by examining three stages of the respective rate loss curves (Fig. 1–3). In the first stage (0–20 min), relatively little runoff, sediment, or carbon loss occurred. The soil surface began to wet up, and splash detachment (estimated as sediment loss before runoff initiation) increased for all treatments, especially for CT-I_c and CT-I_v events (Frauenfeld and Truman, 2004). Conventional tillage had numerically higher splash values (3-fold for I_c, $P = 0.0791$; 28% for I_v, $P = 0.1492$) than ST plots (data not shown). Splash detachment was less for ST compared with CT due to surface residue (4000 kg ha^{-1}). For CT, I_c events had 1.7-fold higher splash values ($P = 0.1547$) than the I_v pattern. Conversely, for ST, I_v events numerically had 18% higher splash values ($P = 0.2861$) than the I_c pattern.

The most dynamic differences or changes occurred in the Tifton soil's surface as a result of the tillage and intensity pattern treatments during the second period (20–40 min). Variable intensity events had more runoff during the first half of the simulation (R_{35}; Table 1) than I_c events. Runoff and sediment yields for I_c events increased steadily throughout this period, approaching steady-state rates by the end of this period (35–40 min) (Fig. 1 and 2). Sediment yield for I_v events increased with runoff and splash detachment peaked at 25 min and then decreased with runoff and splash detachment until the end of the period. Frauenfeld and Truman (2004), while studying the same soil and rainfall intensity pattern under laboratory conditions (CT only), showed that splash sediment for I_c events increased to a relatively constant rate during the 20- to 40-min period. For I_v events, they found that splash detachment rates continued to increase to a peak at about 25 min and then decreased sharply to the end of this period (40 min). They also found that I_v events had more splash detachment during the first half of the simulation than I_c events. As a result of detachment and transport conditions, I_v events have more sediment during the first half of the simulation (E_{35}) and more overall

Table 2. Correlations between runoff, sediment, and sediment carbon content.

Treatment†	Parameters‡			
	$R_{tot} \times E_{tot}$	$R_{tot} \times CER$	$R_{tot} \times C$	$E_{tot} \times CER$
CT-I_c	0.73*	0.92*	0.40	0.74*
ST-I_c	0.76*	0.72*	−0.83*	0.32
CT-I_v	0.91*	0.76*	0.93*	0.46
ST-I_v	0.91*	0.78*	0.66*	0.88*

* Significant at $P = 0.05$.

† CT, conventional tillage; ST, strip-tillage; I_c, constant rainfall intensity; I_v, variable rainfall intensity.

‡ R_{tot}, total runoff; E_{tot}, total soil loss for each event; C, mg sediment carbon per milliliter of runoff; CER, carbon enrichment ratio.

total sediment yield (E_{tot}) (Table 1) than I_c events. Mimicking sediment yield curves (Fig. 2), sediment-transported carbon losses (Fig. 3) during the 20- to 40-min period were numerically higher for CT plots compared with ST plots, with CT-I_v (highest) and ST-I_v plots having higher carbon losses than those for CT-I_c and ST-I_c (lowest) plots. Also, CER values during this period were ∼1 for ST plots (ST-I_v plots had slightly higher CER values compared with ST-I_c plots), whereas CER values during the same period were >2 for CT plots. For CT plots, CT-I_v plots had numerically higher CER values during the 20- to 30-min time period compared with CT-I_c plots, whereas CT-I_c plots generally had numerically higher CER values during the 30- to 40-min period. At the beginning (40–45 min) of the third stage (40–70 min), runoff, sediment, and sediment-transport carbon rate losses crossed (CT-I_v vs CT-I_c and ST-I_v vs ST-I_c) before approaching quasi-steady-state conditions. Constant intensity events had more runoff (R_{70}), sediment (E_{70}), and sediment-transported carbon (C_{70}) in the second half of the simulation than the I_v events.

Differences within each stage occurred because tillage and intensity pattern treatments affected processes controlling runoff, sediment, and carbon losses from the Tifton loamy sand. Sediment yields from the Tifton loamy sand can be transport limited, meaning that transport mechanisms (or the lack of transport mechanisms) control sediment yields. This was true for I_c events in most of the first half of the simulation and I_v events in the second half of the simulation for CT and ST plots. For I_c events, sediment transport capacity was limited by the lack of runoff during the first 35 min, whereas during the second half of each simulation (35–70 min), runoff was established and able to transport sediment. For example, during the last 35 min of I_c events, R_{70}, E_{70}, and C_{70} values were at least 3-fold ($P = 0.0001$), 1.7-fold ($P = 0.0003$–0.0153), and 2.6-fold ($P = 0.0180$) higher than R_{35}, E_{35}, and C_{35} values, resulting in significantly more runoff, sediment, and sediment carbon loss in the second half of I_c events (Table 1). Also, r^2 values for R versus E relationships for CT-I_c, CT-I_v, ST-I_c, and ST-I_v were 0.73, 0.91, 0.76, and 0.91, respectively. Frauenfeld and Truman (2004) reported a r^2 value of 0.81 (splash vs sediment yield) for the CT-I_c treatment on the Tifton loamy sand. Thus, correlations support the concept that transport processes tend to be more important than detachment processes for this soil.

For I_v events, runoff rates peaked late in the first half of the simulation when detachment and transport processes were active and then steadily decreased in the second half of the simulation,

causing the capacity to detach soil and transport sediment to become less toward the end of the simulation. During the first 35 min of I_v events, R_{35}, E_{35}, and C_{35} values were at least 1.3-fold ($P = 0.0001$), 2.3-fold ($P = 0.0001$), and 4.8-fold ($P = 0.0040$–0.0160) higher than R_{70}, E_{70}, and C_{70} values, resulting in significantly more runoff, sediment, and sediment carbon loss in the first half of I_v events (Table 1). Again, detachment and transport processes are active, but transport processes tend to be more important than detachment processes for the Tifton loamy sand.

Also affecting sediment delivery from the Tifton loamy sand is the transportability of the sand fraction of the Ap horizon. About 45% of the sand fraction (85% of the surface soil) in the Ap horizon (0–30 cm) was medium, coarse, or very coarse sand (Perkins et al., 1986). These materials are easily detached yet require much energy to be transported and thus tend to create transport-limiting (depositional) conditions. Small changes in micro-topography and transport capacity (runoff) make these sediments susceptible to deposition, which affects measured sediment yields.

In this study and that of Frauenfeld and Truman (2004), sediment delivery from the Tifton loamy sand was transport-limited under I_c events and was detachment- and transport-limited under I_v events. Strickland et al. (2005) suggested that sediment carbon loss from this same soil is detachment limited, resulting in the greatest carbon losses during the first phase of I_v events. They further suggested that carbon detachment thresholds in response to rainfall intensity patterns may be important to improve risk assessments and predictions of event-based agrichemical transport. Correlations between runoff, sediment, and sediment-transported carbon values (Table 2) support these conclusions and suggest that conversion from CT to ST results in a shift in erosional processes and losses.

In this study, E values were more correlated ($P = 0.05$) with R values under I_v conditions compared with I_c conditions for CT and ST (r^2 values for CT-I_c, CT-I_v, ST-I_c, and ST-I_v were 0.73, 0.91, 0.76, and 0.91, respectively). Although correlations were all significant, the stronger correlation for I_v conditions indicated that sediment yield more closely follows rainfall patterns and that rainfall intensity variation does affect sediment yields under CT and ST conditions. Volume-weighted C values were not correlated or were negatively correlated with R values under I_c conditions ($r^2 = 0.40$ [NS] for CT and −0.83 for ST). Conversely, volume-weighted C values were positively correlated with R values under I_v conditions ($r^2 = 0.93$ for CT and 0.66 for ST). When compared with relationships between R and CER for all tillage-intensity treatments (r^2 values for CT-I_c, CT-I_v, ST-I_c, and ST-I_v were 0.92, 0.76, 0.72, and 0.78, respectively; $P = 0.05$), one can conclude that I_c conditions erode all sediment size classes with no apparent selection of sediment size or CER. There was a correlation between R and CER for CT-I_c ($r^2 = 0.92$; $P = 0.05$) even though no correlation was found between R and volume-weighted C ($r^2 = 0.40$, NS). For ST, kinetic energy associated with raindrop impact is diminished due to surface residue; therefore, detachment- and transport-limiting conditions are created. Thus, r^2 values (E vs R) for ST-I_c and ST-I_v were 0.76 and 0.91, r^2 values (E vs. C) for ST-I_c and ST-I_v were 0.28 and 0.88, and r^2 values (R vs. volume-weighted C) for ST-I_c

and ST-I_v were –0.83 and 0.66. We suggest that ST-I_c had diluted carbon enrichment and that ST systems, in general, have increased particle/aggregate stability that are high in carbon, yet only those less–carbon-enriched particles or aggregates are lost during an erosion event. This explanation is also supported by Fig. 4 where CT CER values are consistently above 1.0 after runoff initiation, whereas ST-CER values only reach 1.0 at the peak of I_v events.

The concept that ST systems change erosion dynamics from detachment- to transport-limiting conditions is also supported by correlations between E and CER. For CT, sediment had a higher CER under I_c events ($r^2 = 0.74$; $P = 0.05$) compared with I_v events ($r^2 = 0.46$, NS). Conversely, for ST plots, no significant correlation was found for E versus CER for I_c events ($r^2 = 0.32$), whereas for I_v events, a significant ($P = 0.05$) correlation was found ($r^2 = 0.88$). Based on our findings, it may be necessary to incorporate variable intensity patterns derived from natural rainfall into rainfall simulations to accurately quantify sediment and carbon yields from agricultural fields, especially under ST systems. When I_c events are used, the lack of correlation between R and volume-weighted C under CT conditions is enhanced from no correlation to a significant negative correlation on converting to ST. Thus, findings suggest that Strickland et al. (2005) and Wan and El-Swaify (1998) may have observed an artifact of I_c conditions when suggesting that sediment becomes less enriched in carbon due to a depletion of carbon rich particles or aggregates with time during an event. However, findings lend further support to the hypothesis of Strickland et al. (2005) in that in regions with relatively short-duration, high-intensity rainfall events, substantial carbon loss may occur only by storms above a certain size and pattern threshold and that such thresholds become more important on conversion from CT to ST systems.

Results from this study show the pronounced effect of tillage system on runoff, sediment, and sediment-transported carbon and illustrate an important point regarding the use of constant intensities compared with variable intensity patterns. That is, models developed to predict runoff, sediment yield, and agrichemical losses may underpredict these variables when they are developed from rainfall simulation studies using constant rainfall intensities. In our case, using I_v rather than I_c would have resulted in a comparable prediction of runoff (difference, 4–10%) but a higher prediction of total sediment and carbon losses by 19 to 36% and 51 to 74%, respectively. Also, I_v events generally produced more runoff, sediment, and sediment-transported carbon losses early in the event, whereas I_c events produced higher losses later in the event, which would affect agrichemical transport and its prediction. With I_c events, the agrichemical has more time to move away from the soil surface, thus not being available for transport by runoff. A more accurate measure and better understanding of the partitioning, entrainment, enrichment, and transport of runoff, sediment, and sediment-transported carbon was obtained when variable intensity patterns derived from natural rainfall were used in rainfall simulation studies. Subsequently, processes controlling partitioning, entrainment, enrichment, and transport of commonly applied agrichemicals would be better understood and improved models could be developed to predict their fate and transport, along with incorporating reduced tillage

systems (ST), as best management practices to remediate problem agricultural fields.

Summary and Conclusions

We compared the effects of I_c and I_v patterns on runoff, sediment, and carbon losses from a Tifton loamy sand managed under CT and ST systems. Four treatments were evaluated: CT-I_c, CT-I_v, ST-I_c, ST-I_v, each replicated three times. Each 6-m^2 field plot received simulated rainfall at a constant (57 mm h^{-1}) or variable rainfall intensity pattern for 70 min. Total rainfall volume was similar for I_c and I_v patterns.

Compared with CT, ST decreased R by 2.5-fold, E by 3.5-fold, and C by 7-fold while maintaining infiltration. Strip-till plots had 82% of the total amount of rainfall that fell to infiltrate, compared with 58% for CT plots; thus, ST plots would have an estimated 42% more days of water for crop use compared with CT plots.

Values of R_{max}, E_{max}, and C_{max} for I_v events were 1.6-fold, 3-fold, and 4-fold higher than corresponding values for I_c events, respectively. Also, R_{max}, E_{max}, and C_{max} for I_v events occurred 38 min, 4 to 11 min, and 18 to 23 min before corresponding values for I_c events, respectively. Values of E_{tot} and C_{tot} for I_v events were 19 to 36% and 1.5-fold higher than corresponding values for I_c events.

During the first 35 min of simulated rainfall, more runoff (34–37%), sediment (37–43%), and sediment-transported carbon losses (55–57%) occurred from I_v events than from I_c events. Thus, R_{70}, E_{70}, and C_{70} values for I_c events were at least 70% higher than R_{35}, E_{35}, and C_{35} values, and R_{35}, E_{35}, and C_{35} values for I_v events were 1.3 to 2.3 times higher than R_{70}, E_{70}, and C_{70} values.

Carbon enrichment ratios were mostly ≤1.0 for ST plots and ≥1.0 for CT plots. Maximum CER values for CT-I_c, CT-I_v, ST-I_c, and ST-I_v were 2.0, 2.2, 1.0, and 1.2, respectively.

Results from this study show the pronounced effect of tillage system on runoff, sediment, and sediment-transported carbon and illustrate an important point regarding the use of constant intensities compared with variable intensity patterns. Models developed to predict runoff, sediment, and agrichemical losses may underpredict when they are developed from data from rainfall simulation studies using constant rainfall intensities. Using I_v rather than I_c would have resulted in a comparable prediction of runoff (difference, 4–10%), higher prediction of sediment yield by 19 to 36%, and a higher prediction of total carbon loss by at least 1.5-fold. Variable intensity events generally produced more runoff, sediment, and sediment-transported carbon results early in the event, whereas I_c events produced more runoff, sediment, and sediment-transported carbon later in the event. For I_c events, the agrichemical has more time to be moved away from the soil surface, thus not being available for transport. This would affect agrichemical transport and its prediction. Processes controlling partitioning, entrainment, enrichment, and transport of runoff, sediment, sediment-transported carbon, and commonly applied agrichemicals (e.g., nutrients, pesticides, antibiotics, nonylphenols) would be better understood if variable intensity patterns derived from natural rainfall were used in rainfall simulation studies to evaluate their fate and transport from CT and ST systems.

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